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REPORT 76-41

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November 1976

REPORT DOCUMENTATION PAGE

**READ INSTRUCTIONS
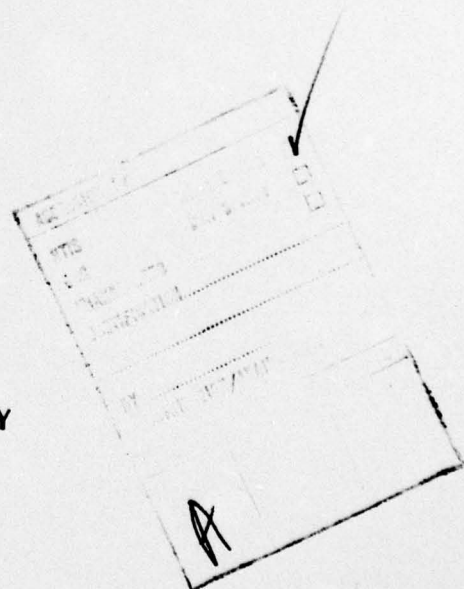BEFORE COMPLETING FORM**

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
CRREL Report 76-41		

4. TITLE *(and Subtitle)*	5. TYPE OF REPORT & PERIOD COVERED
GEODETIC POSITIONS OF BOREHOLE SITES OF THE GREENLAND ICE SHEET PROGRAM	
	6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s)
Steven J. Mock	NSF Grants AG-378 and AG-248

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755	

11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE
National Science Foundation Washington, D.C.	November 1976
	13. NUMBER OF PAGES
	13

14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*	15. SECURITY CLASS. *(of this report)*
	Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

*NSF-AG-378,
NSF-AG-248*

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Borehole sites
Geodesy
Ice observations
Ice strain
Ice velocities

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
Eight Geoceiver stations were established and suitably marked along or near the crestline of the Greenland ice sheet during GISP field operations from 1971 to 1975. At one of these stations, DYE-3, repeated Geoceiver positions indicate an ice velocity of 12.7 m/yr on an azimuth of approximately 60°. Data from the International Greenland Glaciological Expedition (EGIG) surveys show that ice flow in the vicinity of Crete is radiating outward from a dome to the south. Two independent calculations of the state of equilibrium at Crete indicate ice sheet *thinning* rates of 0.25 to 0.37 m/yr, while direct measurement of elevation change by EGIG indicates an ice sheet *thickening* rate of ~ 0.06 m/yr. Resolution of these differences must await further geophysical work and deep drilling in the ice sheet.

DD `1 JAN 73` FORM **1473** EDITION OF 1 NOV 65 IS OBSOLETE

PREFACE

This report was prepared by Dr. Steven J. Mock, Geologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Dr. Samuel C. Colbeck of USA CRREL participated in the 1972 and 1973 field programs.

Technical review of this report was performed by Stephen F. Ackley and Dr. Anthony J. Gow of USA CRREL.

The author wishes to acknowledge the assistance of the Satellite Surveys Branch of the U.S. Defense Mapping Agency (Bert Sharpe, Chief) and the following individuals of USDMA, all of whom, during various field seasons, were responsible for Geoceiver operations: Edward O. Hipsley, Thomas Klockenbrink, Manuel Quintero, William Young and Kenneth Croissant.

SUMMARY

Eight Geoceiver stations have been established along or near the crestline of
the Greenland ice sheet as part of the Greenland Ice Sheet Program. The Geoceiver
is a portable doppler *geo*detic re*ceiver*, receiving and recording signals broadcast by
the earth-orbiting transit satellites of the U.S. Navy Navigational Satellite System.
Processing of the data enables the position of the antenna in an earth-centered
coordinate system to be specified with accuracies approaching ± 1 m.

The stations were established primarily to determine ice velocities, but they also
serve as navigational checkpoints for radio-echo ice-sounding flights. Since the ice
is in constant motion, the ice velocity can be determined by measuring successive
positions of a suitable marker embedded in the ice. To date, only one station,
DYE-3, has had a second-position determination necessary to determine the ice
velocity. In this case, three positions were determined, resulting in two ice velocity
measurements. These velocities were consistent with each other, and a velocity of
12.7 m yr^{-1} was adopted.

Data from earlier expeditions have been used to calculate the state of equilibri-
um of the ice sheet in central Greenland. Two independent calculations give
change of ice thickness rates of $- 0.25$ m yr^{-1} and $- 0.37$ m yr^{-1}, while optical
leveling indicates a rate of $+ 0.06$ m yr^{-1}. Ice velocity vectors near Crete indicate
that the ice is emanating from a dome of outflow to the south rather than from
a dome to the north as had been expected. This bears directly upon site selection
for a proposed deep borehole to penetrate the ice sheet.

GEODETIC POSITIONS OF BOREHOLE SITES OF THE GREENLAND ICE SHEET PROGRAM

Steven J. Mock

INTRODUCTION

The Greenland Ice Sheet Program (GISP) was begun in the summer of 1971 with the successful recovery of 373 m of core from a borehole drilled at DYE-3, Greenland, and the installation and initial survey of a network extending some 16 km up the flowline from the borehole site. Among the objectives of GISP, other than the program of intermediate and deep drilling, was the requirement to provide ice strain and velocity information at drill sites as well as at other locations for modeling and assessing the state of the ice sheet's equilibrium.

The measurement of surface strain rates on a large ice sheet is easily and routinely accomplished by conventional survey techniques. On the other hand, ice velocity determinations have always presented the considerable problem of how to measure the change in position of markers when the fixed points nearest the markers could be up to several hundred kilometers distant. Despite attempts to use indirect techniques such as repeated gravity measurements or seismic surveys to detect systematic changes in bedrock configuration relative to a marked surface area, the only practical method has remained that of carrying conventional surveys from fixed points over the ice sheet to the points of interest. Even repeated first-order astronomic positionings have given ambiguous results.

The advent of the space age promised to alleviate this problem, and with the development of the U.S. Navy Navigational Satellite System, these promises have come to fruition. This report briefly describes this system, the principles of utilizing it for positioning markers, and the positioning program that has been carried out during four GISP field seasons.

U.S. NAVY NAVIGATIONAL SATELLITE SYSTEM

At the present time the Navy Navigational Satellite System (NNSS) consists of six satellites in circular polar orbits. The satellites continuously transmit information, with each message beginning and ending on every even minute. The information consists of two stable carrier frequencies of approximately 150 and 400 MHz, timing signals and the satellites' predicted orbital parameters.

The Geoceiver (*geo*detic re*ceiver*) is one of several instruments designed to receive, transform, and record satellite information for later reduction to geodetic position. The Geoceiver includes a precise internal clock and a stable oscillator whereby the doppler shift of received frequency can be measured over accurately timed intervals. The doppler shift in turn is used to calculate range changes from satellite to Geoceiver which, since the satellite position is known, define the position of the Geoceiver.

Geoceiver operations in Greenland have used the point positioning technique (Defense Mapping Agency 1972), in which a geodetic position is derived without reference to any other positions except those of the satellites. To achieve geodetic accuracies, the predicted orbital parameters (broadcast ephemeris) transmitted by the satellites are not used; instead, a precise ephemeris, calculated from data from a worldwide network of tracking stations, is used for position calculation.

The advantage of point positioning, using the precise ephemeris, is that only a single Geoceiver need be deployed, while to achieve comparable accuracies, using the broadcast ephemeris, requires a minimum of two, or normally more, instruments. The disadvantages of

the point-positioning mode of operation are that real time positions are not obtainable and that normally a precise ephemeris is prepared for only one of the six satellites. Since 30 to 40 satellite passes are required for a strong position, utilizing only a single satellite increases the time on station necessary. This is alleviated to some extent by the high-latitude location of Greenland, where the number of passes per given time interval is substantially greater than at mid or low latitudes.

GREENLAND OPERATIONS

A summary of stations occupied on the Greenland ice sheet is given in Table I and station locations are shown in Figure 1. Note that the elevations given in Table I are heights above the reference ellipsoid, not above mean sea level. Elevations will be discussed more fully in a later section following a brief description of each station.

Northsite

Northsite was occupied for approximately 4 hours on 29 July 1972. This station, located near the crest

of the ice sheet, has a 15-m snow temperature (approximately the mean annual air temperature) of $-31°C$ and an accumulation rate of 16 cm ice yr^{-1} (Dansgaard et al. 1973). Ice thickness in the vicinity is about 3070 m (Gudmandsen 1973).

Four satellite passes were used for the position solution. The site was marked by 4 aluminum poles approximately 4 m high at the time. The poles were spaced 1 m apart, with the southernmost marking the Geoceiver position (see Fig. 2). Based on the typical depth-density profiles (see Benson 1962), the poles should remain visible for about 10 years or until 1982 (1972-1982).

Crete

Crete was occupied for approximately four hours on 1 August 1972. The Geoceiver was set up at pole T43 of the International Greenland Glaciological Expedition (EGIG) (see Fig. 3). T43 marks the crest of the ice sheet based on optical leveling completed in 1959 (Malzer 1968). Ice thickness at Crete is 3150 m with a smooth subice surface (Gudmandsen 1973).

Table I. Geoceiver station data.

Station	Date	Latitude (north)	Longitude (west)	Elevation* (m)	Est accuracy (m)
Northsite	29 July 72	75°46'02."942	42°26'34."409	2882.44	5
Crete	1 Aug 72	71°07'13."367	37°18'58."903	3214.14	5
DYE-3†	2 Aug 72	65°11'14."627	43°49'49."729	2517.38	5
DYE-3	4–7 July 73	65°10'59."128	43°49'33."775	2525.18	2
Summit	6–8 June 74	72°17'09."594	37°58'47."187	3244.22	3
DYE-3	17–20 May 75	65°10'59."460	43°49'32."132	2523.75	2
South Dome	29 May–1 June 75	63°32'45."336	44°35'56."551	2861.43	1.5
Saddle South	2–4 June 75	65°40'13."129	44°18'53."782	2536.71	2
Saddle North	7 June 75	66°11'31."648	43°39'44."088	2534.14	–
A1	8 June 75	67°27'18."542	41°58'49."689	2575.94	5

* Elevations are height above ellipsoid to electrical center of antenna; they are approximately 40 m higher than mean sea level elevations.

NWL 9D ellipsoid parameters: a = 6378.145 km
f = 1/298.25 km

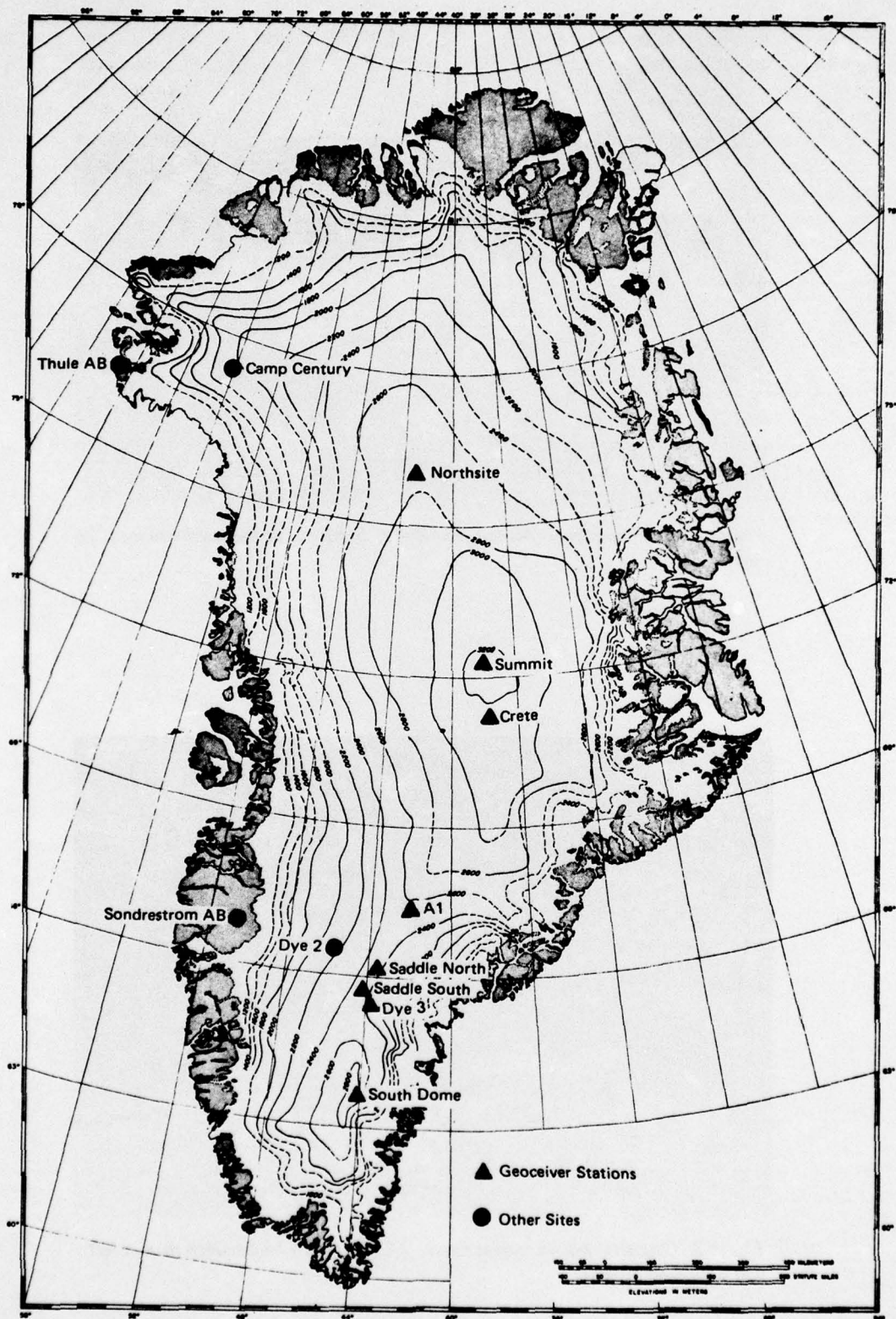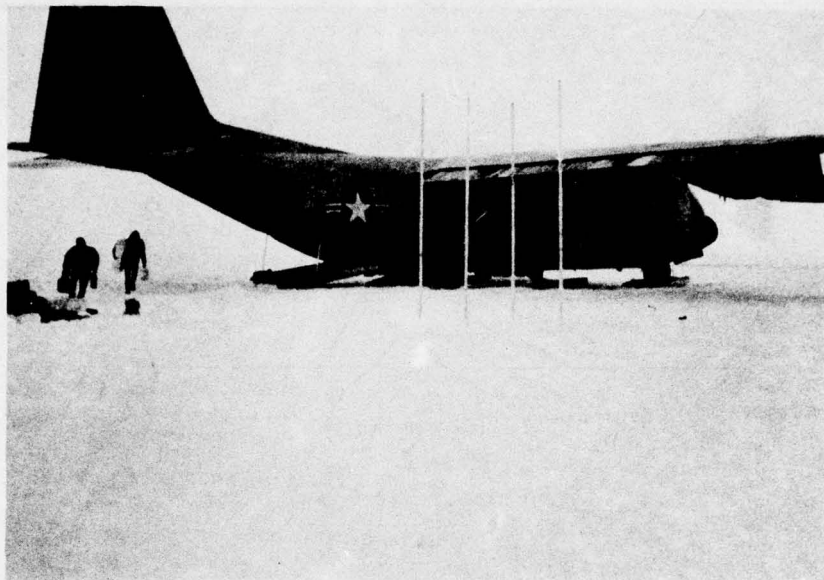† Site changed after 1972 position.

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Figure 1. Location of GISP Geoceiver stations.

Figure 2. Aluminum poles marking Northsite. Station is at the southernmost (far right) pole.

Figure 3. Geoceiver positioning at Crete. EGIG pole T43 is between man at left and Geoceiver antenna.
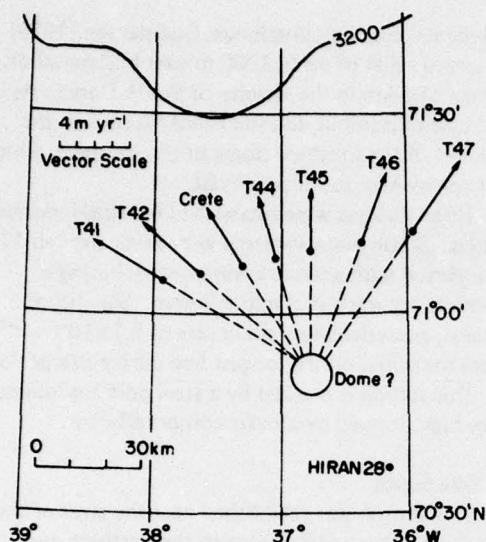
Figure 4. Velocity vectors of EGIG stations in the vicinity of Crete.

A 404-m core was obtained at Crete in 1974. No surface glaciological program was planned, however, inasmuch as results from the EGIG programs were expected to satisfy the GISP requirements. Results of several of these programs have been published and are of considerable interest, particularly as to how they relate to potential sites for deep drilling to the base of the ice sheet.

Figure 4 shows the velocity vectors at Crete and nearby stations as determined from the EGIG surveys of 1959 and 1967 (Hofmann 1974). These vectors indicate that a dome of outflow exists to the south of Crete; this is somewhat unexpected, since the summit of the ice sheet is generally considered to be north of Crete. In Figure 4 the velocity vectors have been projected upstream as straight lines to the area where they mutually intersect, an area of less than 10 km width, some 36 km south-southeast of Crete.

Table I shows that Summit station, to the north of Crete, is at a higher elevation than Crete, as expected from available maps. The velocity vectors in Figure 4 imply that a dome of outflow exists to the south of Crete. This suggests that the crestal region in central Greenland is not generally linear but consists of at least two and possibly more discrete domes.

Using the EGIG data and the assumed position of the dome, it is possible to calculate the state of ice sheet equilibrium in the Crete area by two essentially independent methods:

$$\frac{\partial h}{\partial t} = \dot{a} - h\left(\dot{\epsilon}_x + \dot{\epsilon}_y\right) - u_x \frac{\partial h}{\partial x} \tag{1}$$

or

$$\frac{\partial h}{\partial t} = \bar{\dot{a}} - \frac{sh\bar{u}_x}{S} \tag{2}$$

where h = ice thickness
  $\dot{a}$ = accumulation rate
  u_x = velocity
  $\dot{\epsilon}_x, \dot{\epsilon}_y$ = longitudinal and transverse strain rates
    respectively
  s = distance between two flowlines
  S = area between two flowlines
  $\bar{\dot{a}}$ = mean accumulation rate over S
  $\bar{u}_x$ = mean ice velocity along s.

Table II contains the data and results of these calculations.

Table II. Data for ice equilibrium calculations. Strain rates are from Karsten and Stober (1975), velocities from Hofmann (1974).

Parameters	Crete (eq 1)	Crete-T44 (eq 2)
$\dot{a}$	~ 0.30 m yr^{-1}	
$\bar{\dot{a}}$		~ 0.30 m yr^{-1}
h	~ 3150 m	~ 3100 m
$\partial h/\partial x$	~ 0	
$\dot{\epsilon}_x + \dot{\epsilon}_y$	1.74×10^{-4} m yr^{-1}	
u_x	3.86 m yr^{-1}	
$\bar{u}_x$		3.70 m yr^{-1}
s		10^4 m
S		170×10^6 m^2
$\partial h/\partial t$	-0.25 m yr^{-1}	-0.37 m yr^{-1}

It is assumed in Table II that maximum shear strains are concentrated near the base and that the surface velocity is a good estimate of the mean velocity throughout the column. However, certain of the other data in Table II are, at best, approximations. The ice thickness gradient at Crete is not known in the direction of flow and the basal conditions are completely unknown. These two calculations agree in sign if not in magnitude, both indicating thinning of the ice sheet. On the other hand, results of the EGIG optical levelings indicate that the elevation at Crete increased by 0.5 m in the 9-year interval between surveys (Seckel and Stober 1968), which leaves knowledge of the state of equilibrium in

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somewhat of a quandary. A second Geoceiver position at Crete may help to resolve this problem.

DYE-3

Three separate Geoceiver positions have been established at DYE-3. The 1972 position was made at station 1 of the DYE-3 strain network over a period of approximately 5 hours. The two later positions, each made over a 3-day period, were made at a point close to the DYE-3 radar station. The 1972 station was later referenced to the newer site by survey. The ice velocities obtained from the three fixes are given in Table III.

Table III. Ice velocities at DYE-3 from doppler positions.

Period	Velocity $(m\ yr^{-1})$	Azimuth $(°)$
1972-73	11.8	56
1973-75	12.7	61

Considering that the 1972 position was based on only 4 satellite passes, while the latter two used 30 to 40 passes, the consistency of the two velocity solutions is quite satisfactory. Unfortunately, the change in elevation between the 1973 and 1975 positions is meaningless, since the station is in an area where snow removal operations are carried out by DYE station personnel. Results of strain measurements are being reported elsewhere (Mock, in prep).

Summit

This station was selected as being very close to the true summit of the ice sheet as determined from available maps. Surface mapping at the station showed that the ice sheet slopes upward to the northeast for at least 10 km, the limit to which optical leveling was carried.

Satellites were tracked for three days by Geoceiver and the antenna position was marked by a steel pole extending 9.13 m above the 1974 snow surface (see cover photo). A radar corner reflector is mounted on top of the pole. Based on studies of a 29-m core from Summit (Hammer 1975), this pole should remain visible for approximately 17 years, or until 1991.

South Dome

This station was selected as being very close to the summit of the southern dome of the ice sheet. The subice surface is mountainous; Gudmansen (1973) observed relief of up to 1300 m over horizontal distances of 5 km in the vicinity of South Dome. As in the case of Summit, the site is not located on the summit of the southern dome of the ice sheet, which lies somewhere to the northeast.

Three stations were established for strain measurements. Strain measurements were made over an 11-day period with a laser ranging system having a nominal accuracy of 5 mm ± 3 ppm. Significant strains, equivalent to a strain rate of $3.7 \times 10^{-4}\ yr^{-1}$, were measured on the longest line during this period.

This station is marked by a steel pole approximately 4 m high, topped by a radar corner reflector.

Saddle South

This station was established near the crest of the ice sheet in the saddle between the northern and southern domes. Satellite stations for strain measurements were also established. No significant strains were measured over a 10-day period.

The site is marked by a steel pole extending 4.44 m above the snow surface, topped by a radar corner reflector. The maximum positive surface slope is to the west.

Saddle North

This site was occupied for approximately 5 hours on 7 June 1975. Only two satellite passes were observed; thus, there is no estimate of accuracy given in Table I. The station is located near the crest in the saddle between the northern and southern domes of the ice sheet. The maximum positive surface slope is to the west-northwest. The station is marked by a steel pole approximately 4 m high, topped by a radar corner reflector.

A1

Station A1 was occupied for approximately 4 hours on 8 June 1975. The maximum positive surface slope is to the northwest. The station is marked by a steel pole approximately 4 m high, topped by a radar corner reflector.

Station elevations

The elevations shown in Table I are heights above the reference ellipsoid, in this case the Naval Weapons Laboratory (NWL) 9D ellipsoid. In order to determine height above mean sea level (MSL), it is necessary to know the geoid height, defined as the difference between the reference ellipsoid height and mean sea level.

For measuring the change in elevation at a particular site as a function of time, elevations referenced to the ellipsoid are adequate, inasmuch as the geoid height

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variation over the few tens or hundreds of meters which a station might move are negligible. However, for mapping the slope of the ice sheet, particularly near and along the crest, elevations referenced to MSL are necessary to define local domes of outflow.

The Defense Mapping Agency (DMA) was requested to estimate the MSL heights of several of the ice sheet Geoceiver sites. At the time, seven doppler stations for which MSL heights were known had been established in Greenland. Regression equations were developed from these seven stations to predict the deviation of the true geoid height from that calculated from the gravity model used in NWL ephemeris. Using these predictor equations, MSL heights for DYE-3 and Northsite were calculated. Fortunately, the geoid height is reasonably constant around +40 m near the crestline from southern to central Greenland. Thus, for the most part, the elevations shown in Table I are reasonably accurate relative to one another and are on the average approximately 40 m higher than the MSL height.

DISCUSSION

The capabilities of the Geoceiver as a geodetic instrument have received extensive testing (Defense Mapping Agency 1972) and in general have been found very satisfactory. Intrinsically, Geoceiver operations on an ice sheet such as Greenland or Antarctica should present no problems other than those normally encountered in the polar regions. Operations during four different GISP field seasons have demonstrated that this is the case. In fact, as mentioned earlier, the high-latitude position of Greenland is an advantage, in that the number of satellite passes that can be observed during any given period is substantially greater than that at lower latitudes.

Of the eight Geoceiver stations that have been established along or near the crestline of the Greenland ice sheet, only one, DYE-3, has been reoccupied to determine ice velocities. However, this has been done twice at that site, giving very consistent results. As a secondary benefit of the program, the stations have been marked to form bright radar targets, thus serving as navigational checkpoints for low-level radio-echo sounding flights.

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